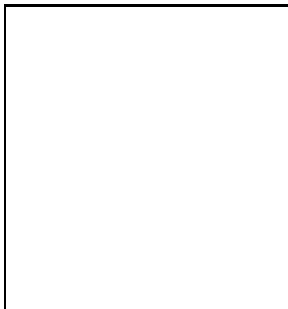


SUNYAEV-ZEL'DOVICH OBSERVATIONS WITH THE RYLE TELESCOPE

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Abstract

The Ryle Telescope has been used to provide images at 15 GHz of the Sunyaev-Zel'dovich decrements towards a dozen clusters in an X-ray luminosity-limited sample. So far, X-ray data have allowed H_0 estimates towards two of these, both giving “low” values that are self-consistent, though it is essential to obtain many more estimates to reduce the effects of cluster projection. We have also discovered a decrement towards the $z = 3.8$ quasar pair PC1643+4631A&B (198” separation); substantial X-ray, optical and infrared follow-up show that the cluster responsible is either at $z > 1$ or very underluminous and that very significant gravitational lensing must be occurring.

1 Introduction

The Ryle Telescope (RT) is being used to carry out a major programme of observations of Sunyaev-Zel'dovich (S-Z) decrements [1] towards clusters of galaxies. This interferometer array consists of 8, 13-m diameter dishes, currently operating at 15 GHz with a 50-K system temperature, and a 350-MHz bandwidth correlator. Interferometers have certain advantages over switched-beam instruments for observations of CMB anisotropy, such as the filtering-out of much of the atmospheric noise, the lack of need for highly stable amplifiers because only correlated power is measured, and the fact that contaminating radiosources can be recognised and subtracted using the longer baselines at the same time and at the same frequency as the S-Z signal is measured — see e.g. [2, 3, 4] ad infinitum. The RT itself has two features that make it particularly suitable for S-Z work. First, its dishes are small: observations at cm-wavelengths are required to make the source contamination manageable, and the angular scales of S-Z decrements thus imply small baselines. Second, the achievement of very long integrations without

systematic offsets was a critical goal throughout all stages of the signal-processing design and construction.

Our main S-Z programme is targetting an unbiased sample of ROSAT-selected clusters with X-ray luminosities $> 10^{37}$ W (0.5-2.5 keV) and with source contamination at 15 GHz of less than 5 mJy. To date we have successful observations of a dozen clusters (see e.g. [5, 6]). I would like to stress that there are of course firm S-Z detections from other instruments, including the OVRO 40-m (e.g. [7]), the OVRO 5-m [8], the OVRO interferometer [9] and SUZIE [10]. There is agreement in observation from a range of techniques, and the business of S-Z observation has moved on from its checkered history to a stage at which observation, though still challenging, is secure.

2 Measuring H_0

A key feature of S-Z astronomy is that, for a given integral of pressure $\int nTdl$ along the line-of-sight through the cluster, the decrement is independent of redshift z . Given that the X-ray surface brightness is a line integral involving n^2 rather than n , combination of X-ray image, S-Z image and T (from X-ray spectroscopy) gives the line-of-sight depth through the cluster. If one can turn this length into one in the plane of the sky, then, knowing z and the angular size, one has a determination of H_0 . The effect of the uncertainty in the change of view from the 90-degree turn is reduced if a suitable sample of clusters is used; the best estimate of H_0 is then the geometric mean of the estimates for each cluster. This is one reason why our S-Z programme concentrates on clusters selected by X-ray luminosity.

In practice, we fit a King profile for n to the X-ray image to give a best-fit gas distribution, simulate the visibilities the RT would measure from this distribution as a function of H_0 , and compute the likelihood function for H_0 . Details of the method are given in [11], which describes its application to A2218.

A2218 seemed to us a sensible choice as our first target for this type of analysis. It is almost circular in projection, so that there is reason to assume its size may be similar along the line-of-sight. It contains no cooling flow. Indeed, on the scales to which the RT is sensitive, it is isothermal and is fitted well by a King distribution. We obtained a value for H_0 of 38^{+18}_{-16} km s $^{-1}$ Mpc $^{-1}$. The individual errors (see below) have been combined in quadrature.

We have applied these methods to another cluster in our sample, A1413 at $z = 0.143$. Its S-Z decrement and other properties are described in [12]. It differs from A2218 in two ways. It has a cooling flow. And it is elliptical in projection, with an axial ratio of 1.3. We are engaged in developing more-sophisticated methods for handling such clusters, but I report here the result of what I emphasise is our first attempt (see [13]) to measure H_0 from A1413. The error budget is as follows (all errors are 1- σ). There is an error in H_0 of 5% from the 3C48/3C286 calibrators (including variability), 25% from RT noise, 10% from source subtraction, 12% from the ASCA estimate of T , and perhaps 4% from a kinetic S-Z contribution. We allow the line-of-sight length to vary between the extreme projected values. Finally there is the issue of gas clumping: the cooling flow implies clumping, and simulations by Steve Allen (private communication) imply the gas temperature may be underestimated by as much as 1 keV, corresponding to an underestimate of H_0 by up to 10%. With all errors combined in quadrature, we find from A1413 that $H_0 = 47^{+20}_{-15}$ km s $^{-1}$ Mpc $^{-1}$. It is worth noting that both A2218 and A1413 (despite its cooling flow) have “well-behaved” X-ray properties on the relevant angular scales.

We have not so far been able to make H_0 determinations for other clusters in our sample because of the lack of available X-ray observations, though this situation is fortunately changing. Our best estimate of H_0 is thus the geometric mean of the values for the two clusters. It will

come as no surprise to many (see [14]) that this is 42.

3 Finding distant clusters

The redshift-independence of S-Z has an even more direct implication: if they exist, one should indeed be able to detect clusters that are too distant to be seen optically or in X-rays. Sunyaev (see e.g.[15]) has long emphasised that deep observation of a patch of sky should reveal an “integrated” S-Z effect from distant clusters. The observational difficulty is that there are no telescopes with the requisite combination of sensitivity and field of view to have a significant chance of detecting a (proto-) cluster in one pointing. We therefore have used the RT to look in the directions of three radio-quiet quasars which, for different reasons, we judged may lie in clusters. We found a decrement towards one of these systems, the quasar pair PC1643+4631A&B which have redshifts of 3.79 and 3.83 and lie 198” apart (see [16]). The 6- σ detection is shown in Fig. 1. The signal is consistently present in different phase and primary-beam pointings and in time-splits of the data, and checks reveal no correlator offsets.

What kind of system might produce this decrement? Such an S-Z signal from the RT gives a *lower* limit to the line integral of pressure through the (proto-) cluster. This is because the least-massive system that can produce such an S-Z effect is one which just fills the synthesised beam: if the cluster is smaller than the beam, there is beam dilution and the “true” S-Z effect and hence cluster mass increase; if the cluster is bigger than the beam, the cluster tends to be resolved out and *again* the “true” S-Z effect and cluster mass increase. Now, if the cluster has $T \sim 5$ keV (like the clusters we know about), then, given the relation between angular size and z , a baryon mass of $10^{14} M_{\odot}$ within a 1-Mpc radius at $z \sim 1$ is the way to produce the S-Z effect that requires the least mass. Given a ratio of total mass to baryon mass of 10, the cluster mass is at least $10^{15} M_{\odot}$.

The next question: is there evidence to support the notion that the massive cluster *is* distant? Evidence so far comes from two fronts. First, PC1643+4631A&B lies on the edge of a pointed ROSAT PSPC field; the upper limit to its X-ray flux corresponds to a luminosity of 7×10^{37} W (similar to the luminosities of nearby clusters in which we see S-Z decrements) at $z > 1$. Second, we have obtained deep R , J and K images of the field with the WHT and UKIRT; there is nothing near the decrement that looks like a cluster at $z < 1$.

It thus appears that, if the cluster is like known luminous clusters, it must lie at $z > 1$ and may be an embarrassment to our standard view of structure formation. Or it may be that the cluster is nearer, in which case it contains far fewer luminous galaxies than known clusters, has gas more rarefied than known clusters (to reduce the X-ray luminosity), yet has a higher gas temperature (to maintain the S-Z).

A system of $10^{15} M_{\odot}$ will gravitationally lens objects behind it. We have carried out simple modelling of the lensing, assuming (and this is not critical) that the lens lies at $z = 1$ and that the gas fits the standard β -model. With a total mass of $1.2 \times 10^{15} M_{\odot}$ within 1 Mpc of the centre, the source (true) positions of quasars A and B almost coincide, despite their observed positions being 3’ apart. A tiny adjustment to the gas distribution model would make the source positions coincident. If A and B really are two images of one quasar, then their spectra should be identical — with two exceptions. Absorption/scattering may be different along the two paths from source to image, and the travel time is likely $\sim 10^3$ years different so that source variability will affect the images. We have obtained high quality optical spectra of A and B: they are remarkably similar, though there are narrow absorption features in them that have the same one-percent redshift difference. We are currently considering a model in which the absorbing gas is in the broad-line region, and that the broad-line velocities we see have not

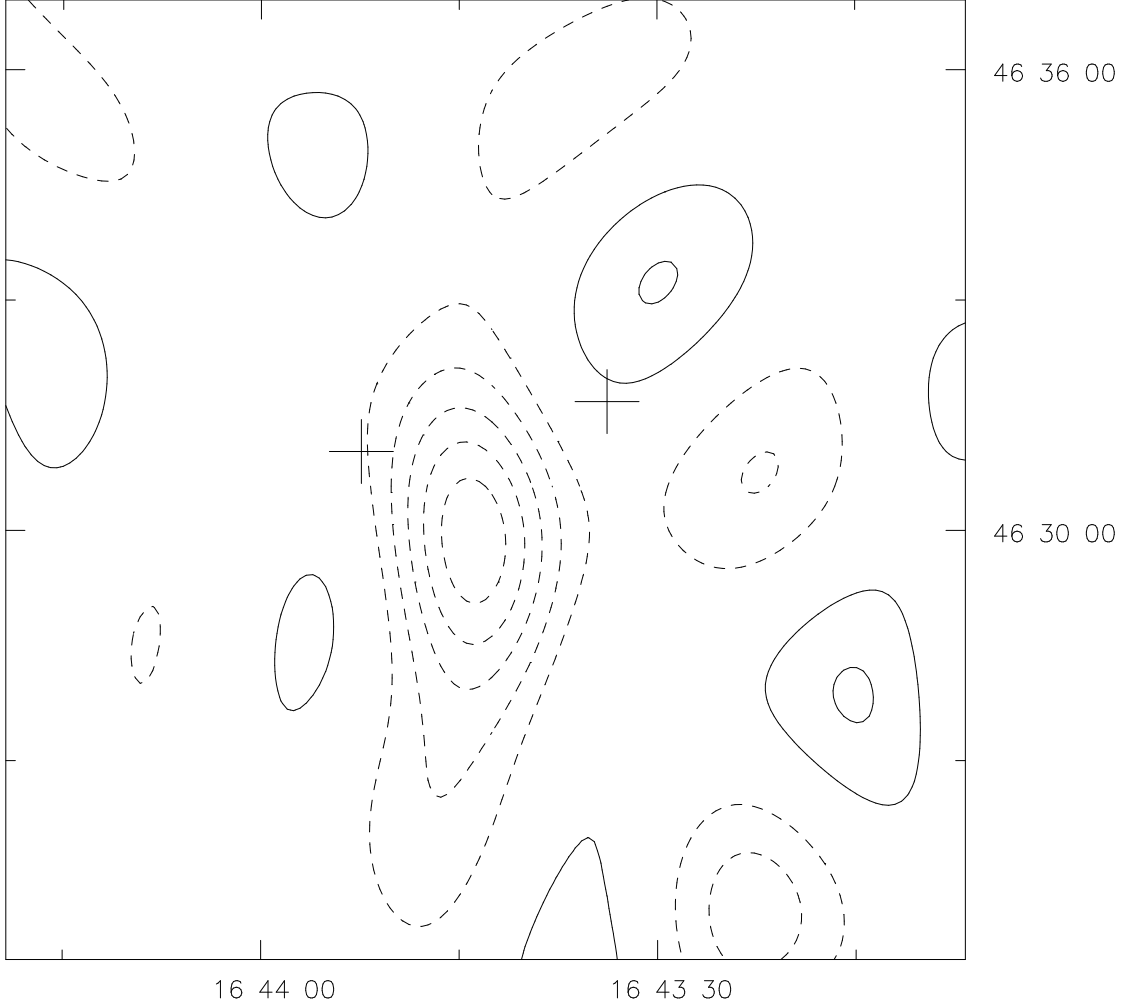


Figure 1: PC16433+4631: CLEANed map of the 0.65–1.25 k λ baseline data after source subtraction. The ‘+’ crosses indicate the positions of quasars A (right) and B (left). Contour levels are -325 to $+130\mu\text{Jy}$ in steps of $65\mu\text{Jy}$; dashed contours are negative. The final map is not corrected for primary-beam attenuation, so the noise level is uniform across the map. Coordinates are B1950.

only a Keplerian component but also a bulk one that changes with time.

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